AN EXPERIMENTAL AND MODEL BASED INVESTIGATION OF THE POTENTIAL AND LIMITATIONS OF SURFACE EMG SPECTRAL ANALYSIS FOR ASSESSMENT OF MOTOR UNIT RECRUITMENT STRATEGY

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Abstract-**Characteristic frequencies of surface EMG power spectrum have been used in the past as indicative of motor unit (MU) recruitment, since they are rather insensitive to changes of MU firing rates and thus they should remain constant when only rate coding is used to modulate muscle force. However, this speculation has not been yet validated by simulated and experimental data. In this paper, a model of surface EMG signal generation and detection is used to simulate EMG signals detected during linearly increasing force contractions. Different MU control strategies (corresponding to different ways for force generation by recruitment and rate coding) are simulated. A number of simulations are performed to study the effect of random distribution of MUs in the muscle's cross-section upon the surface EMG. The results are compared with those obtained analyzing the EMG signals detected experimentally during linearly increasing force contractions of the biceps brachii muscle in 10 subjects. Results show that the volume conductor properties may act as confounding factors which may mask any relationship between characteristic spectral frequencies and conduction velocity as a size principle parameter. It is concluded that more advanced signal processing techniques which aim at the analysis of single MU activity are required for the surface EMG based assessment of central nervous system control strategy.**
***Keywords* - rate coding, surface electromyography, motor unit recruitment, EMG spectral analysis, muscle fiber conduction velocity**

I. INTRODUCTION

Many past studies were devoted to clarify the relationships between global surface EMG variables and the muscle contraction properties in order to extract information of physiological interest from the analysis of the surface EMG signal. It has been established that the value and rate of change of spectral variables and CV during sustained isometric constant force contractions is indicative of muscle fatigue [12] and may be correlated with MU type [14]. It has also been shown, both theoretically [10] and experimentally [1], that, during fatiguing isometric constant force contractions, CV and mean or median spectral frequency (MNF and MDF) of the surface EMG signal are highly correlated, MNF and MDF reflecting mainly (but not only) the changes in CV of the active MUs.

A few more contradictory studies address the possibility of investigating central nervous system (CNS) control strategies by surface EMG. It is well known that CNS uses two variables for the control of muscle force, the recruitment/derecruitment of MUs and the modulation of their firing rates (rate coding). These two mechanisms of force control are present in different proportion in different muscles [8]. It has been speculated that the characteristic frequencies of the surface EMG power spectrum should reflect the recruitment of new, progressively larger and faster MUs, increasing until the end of the recruitment process and maintaining a constant value when only rate coding is present [2]. This hypothesis is based on two theoretical considerations: 1) the CV of a single MU action potential (MUAP) is scaling the power spectrum of that MUAP [10] and 2) the firing rate of a MU has a negligible impact on the frequency content of the surface EMG signal [9]. These two observations are valid when the MU pool is stable but it is not clear within which approximation they can be considered valid during non-constant force contractions. In particular, the effect of the recruitment of a new MU on MNF and MDF is not clear since the contribution of a MUAP to the surface EMG power spectrum depends on the location of the MU in the muscle. The volume conductor acts in fact as a low pass filter whose characteristics are related to the MU depth and to the properties of the subcutaneous tissue layers. Although a large number of studies aimed in the past at the determination of a relationship between EMG power spectrum (or its characteristic frequencies) and force, it is not yet clear which central mechanisms are reflected by the surface EMG variables.

It is the purpose of this paper to investigate the possibilities and limitations of the use of global surface EMG variables as indicators of MU recruitment strategies. The work is divided in a model based and an experimental approach which are strongly interrelated.

II. METHODOLOGY

A. Simulation model

We recently proposed an accurate and fast model for the simulation of the surface EMG signal [5]. The model simulates synthetic MUAPs generated by finite length fibers and detected by surface electrodes with physical dimensions. The volume conductor is an anisotropic and non-homogeneous medium constituted by muscle, fat and skin tissues [4] (Fig. 1a). The simulated signals were detected by the configuration proposed by Broman *et al.* [3], with interelecrode distance of 10 mm and bar electrodes 5 mm long, 1 mm diameter. The detection probe was located at the middle between the center of the innervation zone and of the tendon region of a number of MUs having mean semi-length (in both directions) of 65 mm. The number of fibers of each MU varied between 50 and 450 and the MU fiber density was 20 fibers/mm^2 [6]. The territory of the MUs was assumed to be circular and the fiber density in the muscle was 200 fibers/mm^2. Sixty-five MUs have been simulated in each

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
25OCT2001	N/A	-

Title and Subtitle An Experimental and Model Based Investigation of the Potential and Limitations of Surface EMG Spectral Analysis for Assessment of Motor Unit Recruitment Strategy	**Contract Number**
	Grant Number
	Program Element Number
Author(s)	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Department of Electronics Torino, Italy	**Performing Organization Report Number**
Sponsoring/Monitoring Agency Name(s) and Address(es) US Army Research, Development & Standardization Group (UK) PSC 802 Box 15 FPO AE 09499-1500	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)
Distribution/Availability Statement Approved for public release, distribution unlimited	
Supplementary Notes Papers from the 23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society, October 25-28, 2001, held in Istanbul, Turkey. See also ADM001351 for entire conference on cd-rom.	
Abstract	
Subject Terms	
Report Classification unclassified	**Classification of this page** unclassified
Classification of Abstract unclassified	**Limitation of Abstract** UU
Number of Pages 5	

trial. The recruitment threshold *RTE* (to be interpreted as recruitment instant during a linear ramp isometric contraction) of each MU has been computed as suggested in [6] with the following exponential rule (Fig. 1b):

$$RTE(i) = e^{ai} = e^{\ln(RR)\, i/n} = RR^{i/n} \qquad i=1,2,\ldots,n \qquad (1)$$

where i is an index identifying the MU and a is a coefficient which determines the range of recruitment. In particular, it is $a = (\ln RR)/n$, with n the total number of MUs activated during the contraction and RR the percentage of time during which recruitment of MUs is present with respect to the total contraction time. The size principle [7] has been assumed for the recruitment order with the small and low CV MUs being recruited at the beginning of the contraction. Fatigue was not included in the simulations. The firing rate of each MU was increased linearly in time after recruitment with a slope of 10 pps/s (pps = pulses per second). The minimum firing rate was 8 pps (firing rate at the recruitment) and the maximum firing rate was 35 pps. The mean of CV distribution was 4 m/s while the standard deviation was varied between 0.3 m/s and 0.7 m/s. The CV distribution was a truncated Gaussian with minimum and maximum CV values 2 m/s and 7 m/s.

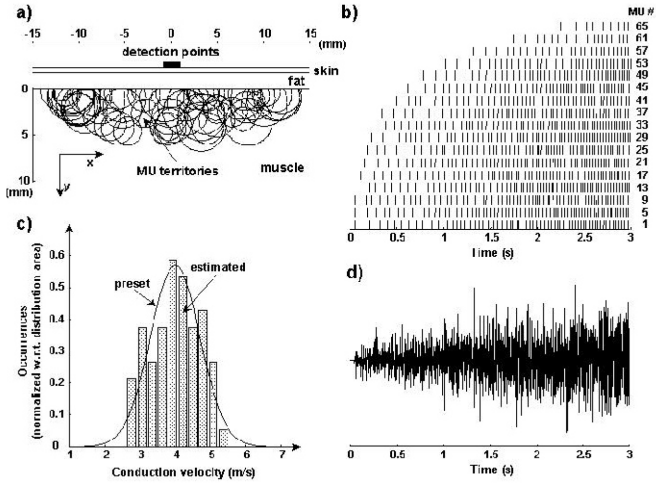

Fig. 1 Example of a single differential signal generated by the model. a) Location of the MUs in the muscle and MU territories. b) Firing patterns of the active MUs (only one firing pattern every four) during a contraction with recruitment up to 75% of the contraction time. c) CV distribution (Gaussian with mean 4 m/s and standard deviation 0.7 m/s) normalized with respect to the distribution area. d) Generated single differential signal. The CV distribution shown in (c) is the distribution of the CVs of all the 65 simulated MUs. Recruitment of these MUs progresses from low CV to high CV.

Each simulation set consisted of 50 synthetic signals; for the generation of each signal in the set the locations of the MUs in the muscle were randomly selected (with uniform distribution in the detection volume) while the firing patterns, CV distribution and number of fibers for each MU were constant for the entire set. The aim was to observe the influence of location of the MUs in the muscle on the estimated EMG variables when the other physiological parameters of interest were fixed.

Simulated signals were processed with the same techniques as the real signals (see below). No noise was added to the synthetic signals.

B. Experimental protocol

Ten male healthy subjects with ages between 22 and 35 years (mean ±std: 26.3 ±4.3 years) participated in the study after giving informed consent. All the subjects were free from neuromuscular diseases. The muscle studied was the biceps brachii of the dominant arm. Torque was measured with a modular brace which incorporates two independent torque meters (mod. TR11, CCT Transducers, Torino, Italy), on each side of the brace. In each experimental session, the subject was asked to produce three maximal voluntary contractions (MVCs) of the duration of 2-3 seconds separated by two minute rest and was encouraged to exceed the previously reached maximum level (visual torque biofeedback was given to the subject when exerting the MVCs). The maximum of the three MVCs was taken as reference. After the MVC measurement, the subject performed a training session consisting of three ramp contractions of the duration of three seconds with linearly increasing force between 0% and 80% MVC. The desired force trajectory was displayed on a computer screen along with the output of the force transducers, providing real time biofeedback for the subject. The acceptable error band for force tracking was ±5% MVC. After the training session ten minute rest were given to the subject who was then asked to perform two additional ramp contractions as those performed during the training session but followed by a constant force contraction at 80% MVC lasting 11 seconds. The 80% MVC was sustained by the subject with the same error band imposed during the ramp contraction (±5% MVC). During these two last contractions the EMG signals were recorded. Ten minute rest were given to the subject between the two contractions. The subject repeated the experimental session in two different days.

In order to obtain reliable estimations of the EMG variables, surface EMG signals were detected with a linear array of 16 electrodes [11][13] (silver bars 10 mm apart, 5 mm long, 1 mm diameter). The EMG signals were amplified and band-pass filtered (3 dB bandwidth: 10 Hz-500 Hz), sampled at 2048 Hz and converted in digital form by a 12 bit A/D converter.

The contraction was divided in two intervals, the ramp and the constant force part. The ramp was defined as the time interval between the instant in which the subject exceeded the 5% MVC and the instant in which the subject exceeded the 75% MVC; the constant force interval was defined as the interval beginning 0.5 seconds after the ramp interval and lasting until the end of the contraction.

III. Results

A. Simulations

Fig. 2 shows MNF and CV versus time for two different recruitment strategies. Three realizations of the 50 simulations performed are shown. The first strategy (left plots) corresponds to recruitment of MUs from the beginning to the end of the contraction, the second strategy (right plots) from the beginning to the 50% of the contraction time. Estimated CV is increasing in all cases. MNF shows different behaviors during time, depending on the MU location in the muscle. It is not possible to distinguish the two recruitment

conditions by looking at the time pattern of MNF. The maximum in MNF curve is also shown for the three cases in the two conditions. It appears that this parameter has a very large variability which reduces its value as indicator of the end of the recruitment process.

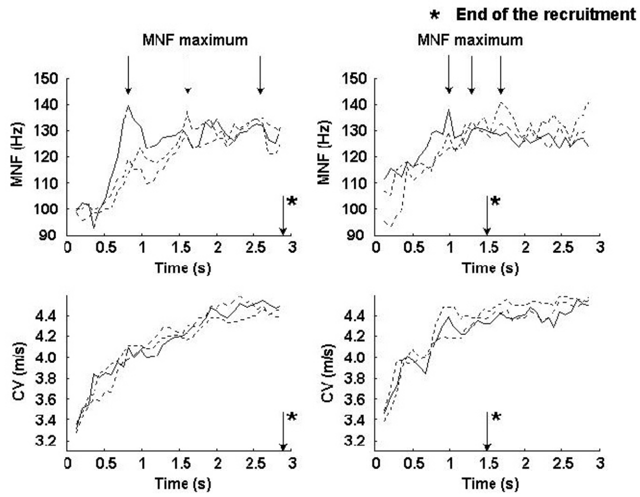

Fig. 2 Results from three (out of 50) signals obtained by simulating two different recruitment strategies. CV distribution standard deviation is 0.7 m/s. Estimated MNF and CV are shown. The set of the three synthetic single differential signals in the two cases have been generated with the same CV distribution, MU sizes and firing pattern; only MU location is different in the three simulations. The end of recruitment is shown in the two cases as well as the MNF maximum point. The two cases represent different recruitment strategies; in the first case (left column) the recruitment of new MUs is present from the beginning until almost the end of the contraction (RR=95 in Eq. (1)) while in the second case (right column) recruitment ends at 50% of the contraction time (RR=50 in Eq. (1)). Note that MNF shows a pattern in time very similar in the two conditions and that the spread of the peaks of MNF is very large in both cases.

Considering the entire simulation set, the maximum MNF value occurred at a time instant (mean ± std) of (61.0 ± 15.1)%, (72.3 ±24.0)% and (71.2 ±22.2)% of the contraction time, for the recruitment until 50%, 75% and 95 % of the contraction time, when CV distribution standard deviation is 0.7 m/s. For the case of CV distribution standard deviation of 0.3 m/s we obtained that the maximum point of MNF was, respectively at (49.0 ±20.5)%, (66.0 ±31.7)% and (57.4 ± 22.0)% for recruitment until 50%, 75% and 95%. It was not possible, for either one of the CV distribution standard deviation values, to statistically distinguish (Student t-test for independent samples, p = 0.05), the recruitment until 75% and 95% of the contraction time, even with 50 cases. It was possible to statistically distinguish (Student t -test for independent samples, p = 0.05) between the recruitment until 50% and 75% of the contraction time with the 50 realizations for both values of CV distribution standard deviation (the difference was not statistically significant when less than 20 realizations were used for the comparison).

The linear regression correlation coefficient (CC) between CV (which can be considered a size principle parameter) and MNF in case of CV distribution standard deviation of 0.3 m/s was (mean ± std) 40.6 ±27.8, 42.9 ± 25.7 and 53.5 ±22.3 for recruitment until 50%, 75% and 95 % of the contraction time. In case of CV distribution standard deviation of 0.7 m/s, CC was 77.2 ±10.2, 71.7 ±15.6 and 81.1 ±9.9 respectively for recruitment until 50%, 75% and 95 % of the contraction time. For small values of CV distribution standard deviation negative values of CC were even observed, indicating that MNF may decrease while global CV is increasing. This may happen when new MUs are recruited far from the electrodes.

B. Experimental data

In the experimental signals estimated CV always increases with force. MNF presents subject dependent behaviors, being constant or initially increasing and remaining stable for the last part of the contraction (Fig. 3). Five subjects showed an increasing MNF until a certain force level and then a constant value. Two subjects presented a constant MNF and two subjects showed MNF increasing until the end of the contraction. In only one case a decrease of MNF (with increasing CV) was observed. In the seven cases of non-constant or decreasing MNF, the MNF maximum was located between 40% and 75% MVC.

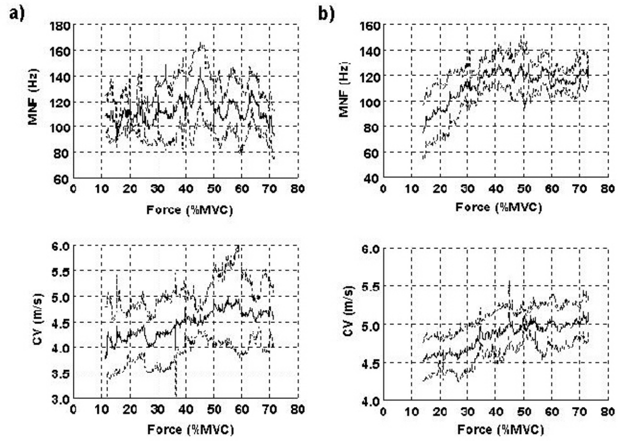

Fig. 3 Representative results obtained during the ramp part of the contraction from two of the 10 investigated subjects. MNF and CV are shown versus force level. The three curves represent the mean ± one standard deviation of the four measurements for each subject. a) MNF is almost constant during the contraction while CV is increasing, b) MNF is increasing until about 40% MVC and then is almost constant while CV is increasing for the entire force range. The other subjects showed a behavior similar to one or the other of those reported in this figure.

Fig. 3 reports representative results obtained from the experimentally detected signals and Fig. 4 shows the scatter plot between CV and MNF for one of the subjects for the ramp and the constant force part of the contraction. Note the higher correlation between the two variables during the constant force contraction. CCs between CV and MNF close to unity were found in all the cases during the constant force contraction (mean ±std: = 81.0 ±12.3, N = 38) while much lower values were obtained during the ramp contractions (mean ±std: 54.1 ±32.5, N = 38).

IV. Discussion

It has been suggested that the recruitment of progressively larger MUs with higher CVs should determine an increase of MNF and MDF, with the maximum value of the two variables indicating the end of the recruitment phase. This hypothesis is based on the claimed linear correlation between MNF or MDF and CV during the recruitment phase. However, the theory of volume conductor and the features of

the EMG variable estimators indicate that the relationship between recruitment and spectral features may be masked by anatomical or geometrical factors and estimation errors. A precise indication of the limitations of surface EMG spectral analysis in recruitment strategy investigation was lacking in literature. In the present study the simulation analysis aimed at investigating the variability of EMG variables due solely to the random location of the MUs in the muscle, an approach which has never been adopted before.

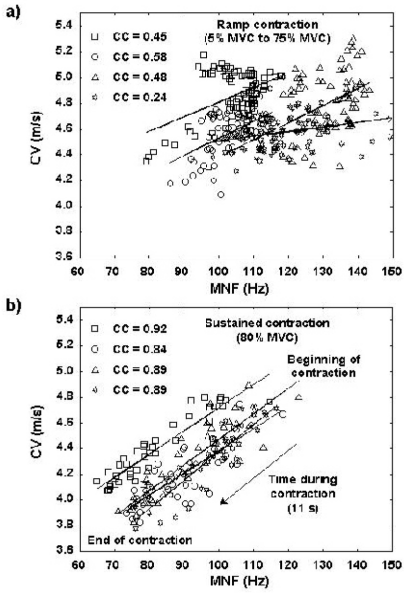

Fig. 4 Scatter plots of CV versus MNF for the four contractions performed by one of the subjects during the ramp (a) and the constant force (b) contraction for the four trials performed. CCs are also reported. Analysis window of 250 ms without overlapping in case of sustained force portion of the contraction, overlapping of 249 samples in case of ramp force part (in this case only one value every 64 is shown for clarity). Each symbol refers to one trial.

Depending on MU location in the muscle it was evident that the correlation between CV and MNF (or MDF) during recruitment may be poor with the consequence that the maximum point of MNF (or MDF) does not necessarily indicate the end of recruitment because of different tissue filtering for different MUAPs. A decrease of spectral variables with recruitment of MUs with progressively higher CVs may even occasionally occur. The large variability of the position of the maximum point of MNF obtained in the simulations was indirectly confirmed by the experimental data since large variability was observed in the position of the MNF maximum in recordings from a muscle which is supposed to recruit MUs up to 80% MVC (the maximum force level reached in the present study). Also the CCs obtained in experimental signals were well in agreement with those obtained in the simulations. On the basis of our findings, an index based on MNF (or MDF) maximum does not seem to reflect phenomena related to central control.

V. Conclusion

The main conclusion of this paper is that surface EMG global variables give poor indications about MU recruitment strategies and considerable caution should be used in the interpretation of these variables as indicators of CNS muscle force control strategies. The presented data do not support the establishment of a general relationship between spectral variables and force or recruitment strategy.

Acknowledgment

This work has been supported by the European Shared Cost Project NEW (QLRT-2000-00139), Fondazione CRT and Compagnia di San Paolo di Torino.

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